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Title: A Benefit-Cost Analysis of Floodplain Land Acquisition to Reduce Flood Damages in the US.

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Abstract: Flooding is the costliest form of natural disaster and impacts are expected to increase, in part, due to exposure of new development to flooding. However, these costs could be reduced through the acquisition and conservation of natural land in floodplains. Here we quantify the benefits and costs of reducing future flood damages in the United States by avoiding development in floodplains. We find that by 2070, cumulative avoided future flood damages exceed the costs of land acquisition for more than one-third of the unprotected natural lands in the 100-year floodplain (areas with a 1% chance of flooding annually). Large areas have an even higher benefit-cost ratio: for 54,433 km^2 of floodplain, avoided damages exceed land acquisition costs by a factor of least 5 to 1. Strategic conservation of floodplains would avoid unnecessarily increasing the economic and human costs of flooding while simultaneously providing multiple ecosystem services.

Text

Flooding is one of the most costly and damaging types of natural hazard in the world[1]. In the US alone, flooding has caused an average of more than $8 billion annually in damages since 2000[2] and future damages are expected to rise due to climate change and continued development in high risk areas[3]. Incomplete and inaccurate mapping of flood risk zones hinders the ability of floodplain managers and planners to guide development to limit exposure and mitigate flood risk. The Federal Emergency Management Agency (FEMA) is tasked with delineating Special Flood Hazard Areas. These are zones projected to be inundated with a 1% annual exceedance probability (AEP) or "100-year" recurrence interval flood event and within which property owners are required to purchase flood insurance under the National Flood Insurance Program (NFIP). However, nearly 40% of the conterminous United States (CONUS) lacks this mapping for riverine floodplains, limiting the potential to plan new development to minimize future fluvial flood risk. Recent research has highlighted the shortcomings of current information and used new comprehensive floodplain mapping, revising estimates of people at risk from a 100-year flood from 13 million to more than 40 million[4].

Flood risk management in the US is not only constrained by incomplete floodplain mapping but also relies heavily on built infrastructure to protect assets in the 100-year floodplain[5]. As many as 160,000 kilometers of levees protect more than $1.3Tn in assets, yet deferred maintenance and delayed repair prompted the American Society of Civil Engineers to give levees in the US a 'D' grade in its most recent report card, indicating that this infrastructure is "in poor to fair condition,… with strong risk of failure"[6]. When impaired and under-designed infrastructure fails, it can have catastrophic results for people and property that were presumed to be protected. This engineered approach to risk mitigation not only potentially exacerbates vulnerability by encouraging development in floodplains. It also disconnects floodplains from the channel, degrading important habitats and reducing the capacity of natural ecosystems to process nutrients, capture sediment, sequester carbon, recharge aquifers and perform a range of other critical functions[7]. The loss and degradation of these ecosystems reduces the multiple benefits that people derive from healthy rivers and floodplains and can exacerbate flood risk in other parts of the river system[8, 9]. Recent analyses demonstrate the potential for floodplain protection and restoration to help reduce risk at specific sites or river reaches[10, 11], yet information does not exist to incorporate this strategy into regional decision-making and target efficient use of limited resources.

To address this gap, we quantified the potential future flood damages that could be avoided by conserving current natural lands in floodplains, some of which are projected for development by 2050 and 2070. We used the output from a new continental-scale hydrodynamic model[12] together with the National Land Cover Database (NLCD) to quantify the area of natural lands (forests, wetlands and grasslands) in riverine floodplains in the conterminous US. We then used the Protected Area Database of the US (PADUS) and the US Environmental Protection Agency (USEPA) Integrated Climate and Land Use Scenarios (ICLUS) of projected development patterns to identify areas of natural land cover in US floodplains that are not currently protected and are also projected to be developed. The hydrodynamic model enables locally accurate mapping of floodplains associated with varying frequencies of flood events at high resolution (1 arc second, ~30 m). We conducted spatial and economic analyses for 5 different flood probabilities: the 20% AEP event or 5-year flood; the 5% AEP (20-year); the 2% AEP (50-year); the 1% AEP (100-year), and the 0.2% AEP (500-year) flood event. We identified more than 675,919 km^2 of natural lands in the 100-year floodplain across the conterminous US that are not currently in some form of protected status, while the 5-year floodplain contains more than 371,129 km^2 of similarly unprotected natural lands (Table 1). Only a portion of these areas are projected to be developed by 2050 or 2070 under either of the two ICLUS future population growth and development scenarios considered in this analysis. In the 100-year floodplain, 141,449 km^2 and 127,928 km^2 are projected to be developed by 2050 under the SSP5 (fossil-fueled development) and SSP2 (middle of the road) scenarios respectively. Results in the main text are based on SSP2, the middle-of-the-road scenario. Results from the higher-development scenario (SSP5), which show greater avoided damages and therefore greater benefits of floodplain protection, are presented in the Supplementary Materials.

The projected new development in floodplains would increase the number of assets at risk and thus the associated damages from flood events. We used the FEMA National Structure Inventory and the National Land Use Dataset[13] to develop a per-pixel asset value of current developments, and iterated these values across the ICLUS land use projections. To estimate the economic impact of future floods we applied depth-damage functions from the US Army Corps of Engineers to quantify the expected damages to projected development from future flood events. We estimated the average annual losses (AAL) within each of the five floodplain boundaries for each year from 2018 to 2070. Since future development is projected to occur gradually we calculated the AALs for each year to capture the timing of expected increases in exposure and damages. We then calculated the present value (PV) of potential damages from all future flood events through both 2050 and 2070 using a standard 2.75% discount rate for water resources planning and evaluation[14] as well as a higher 5% and a variable declining discount rate. The PV of future flood damages by 2070 ranges from \$136 to \$225 Bn in the 5-year floodplain and from \$368 to \$608 Bn in the 500-year floodplain, depending on the discount rate applied (see Supplementary Materials).

However, these potential damages could be reduced if some of the currently unprotected natural floodplain lands were conserved and future development instead occurred outside of floodplains. Land acquisition is a strategy to prevent potential future development in areas that are at risk of flooding and to ensure open space is conserved. Other strategies, such as more restrictive zoning or establishment of conservation easements, could also avoid future development, but we quantified the cost to acquire all currently unprotected floodplain areas to provide an upper-limit estimate of the cost of avoiding these future flood damages through land acquisition. We developed a new county-level land cost layer for the CONUS based on actual parcel-level transactions made for conservation purposes, agricultural land prices from the US Department of Agriculture's 2017 Census of Agriculture[15], and developed land prices from Davis et al.[16], to estimate the acquisition cost of currently unprotected natural lands within floodplains for the flood events analyzed. Our estimates of acquisition cost represent the upper bound of the opportunity cost of floodplain protection; that is, the highest-value non-conservation land use foregone due to conservation (e.g., agriculture, developed). We calculated acquisition costs and damages for multiple floodplain areas corresponding with the 5-year, 20-year, 50-year, 100-year and 500-year flood zones. We then compared PV damage reductions and land acquisition costs within each floodplain (e.g. 5-year extent, 20-year extent, etc.). All dollar values used in the analysis and reported in the paper are for 2018.

Purchasing the 675,919 km^2 of unprotected natural lands in the 100-year floodplain would cost \$306 Bn and purchasing all of the 371,129 km^2 of unprotected natural lands in the 5-

year floodplain would cost \$172 Bn. We tallied the cost of acquiring all of the unprotected natural lands in the floodplains (not only those places projected to be developed in the ICLUS data) to account for uncertainty in development projections and because protecting only the specific lands projected to be developed would likely induce partial displacement (leakage) of development to other natural floodplain areas not currently identified in development projections. While our land prices reflect opportunity costs, including the option value of future development,[17, 18] we explored the impact on results of adding an additional opportunity cost of 1.4% of the county-level mean price for residential land and structures, which we estimate is equivalent to the mean loss in residential amenity values associated with proximity to rivers that owners or developers of displaced properties may incur (see Supplementary Information). However, protection of floodplains may not result in net loss of aggregate amenity benefit as displacement of development increases open space and associated home value premiums for remaining residential properties just outside the floodplain[19].

Comparing the floodplain acquisition costs to the flood damages associated with projected development, we find positive benefit:cost ratios (BCRs) for this floodplain conservation strategy for most, but not all, combinations of flood probabilities and discount rates evaluated for both 30-year (i.e. to 2050) and 50-year (i.e. to 2070) time horizons (Table SI1). At the scale of the conterminous US, using a 2.75% discount rate to compare floodplain acquisition to cumulative potential damages avoided by 2070, we calculate average BCRs ranging from 1.3 for acquiring floodplains in the 5-year floodplain to 2.2 for acquiring floodplains in the 20-year floodplain (Figure 1). The strategy is also generally cost-effective even when evaluated over a shorter, 30-year time period, with average BCRs ranging from 1.1 for acquiring all floodplains in the 500-year floodplain to 1.5 for acquiring all floodplains in the 20-year floodplain; the one exception being the 5-year floodplain, which at the scale of the conterminous US has an average BCR of 0.9. For a higher discount rate of 5% and a 30-yr time horizon, acquisition costs exceed the benefits of avoided flood damages for most flood probability zones, with the exception of the 20-year floodplain where the average BCR still exceeds 1. However, when the strategy is evaluated with a longer time horizon and accounts for potential damages out to 2070, floodplain acquisition is expected to be cost-effective across almost all flood probability and discount rate combinations. These findings are robust to higher costs that include the additional 1.4% opportunity cost: at the scale of the CONUS and under the standard discount rate, protection yields net benefits for all but the 5-year floodplain area over the 50-year horizon, and all but the 5-year and 500-year areas over a 30-year horizon (Figure SI4).

Although conserving floodplains to avoid damages from projected development is a strategy that produces net economic benefits across wide regions of the US (Figure 3), it is most cost-effective and produces the highest net present value (NPV) benefits when targeted to conservation of the region between the 5% and 20% AEP zones (Figure 2). The avoided flood damages in this area exceed the costs of acquiring these additional 158,786 km^2 of unprotected natural floodplain by a factor of 2.9 by 2050 and 4.3 by 2070 using the 2.75% standard discount rate (Table 1), with NPVs of \$133 Bn and \$233 Bn, respectively. Although the 5-year floodplain inundates more frequently, projected development is greater in the area beyond the 5-year but within the 20-year floodplain, making this zone the economically optimal area to target for conservation. Additionally, our results indicate that floodplain conservation is most cost-effective when targeted to certain areas of the country. Counties with the most projected new development, with the lowest land costs and that also experience frequent flooding show up as the places where floodplain acquisition would likely yield the greatest BCR. Across the CONUS, the total BCR for acquiring land in the 20-year floodplain to avoid damages by 2070 is 2.2, yet floodplain acquisition is only cost-effective in the 55% of counties that have a BCR greater than 1. This strategy would be particularly effective in 36% of counties that have a BCR exceeding 2 and even more cost-effective in 13% of counties that have a BCR greater than 5. Regions of the country where floodplain protection generates particularly large net benefits include the southwestern US, the eastern Great Lakes, the Appalachians, and the areas around Miami and Houston (Figure 3).

This analysis highlights the opportunity to mitigate future flood risk in the CONUS through targeted land conservation in riverine floodplains. We find that a strategy of floodplain acquisition would be economically justified when compared to the present value of avoided flood damages projected to occur by 2070. Our estimate of costs is likely high since it presumes the direct purchase of all of the currently unprotected natural lands in floodplains. Use of conservation easements or changes in zoning or land use regulations could achieve floodplain conservation at a much lower cost[20]. Moreover, our estimate of benefits is likely low because floods impose a wide range of additional costs on society beyond the direct damages to building structures considered in our analysis[21]. Total damages likely would be at least 25% higher than our estimates of avoided direct damages, and possibly substantially more for larger flood events[22, 23]. Our estimate of damages does not account for potential protection that could be provided by additional flood defense mechanisms and likely overestimates damages in areas where development behind levees would be protected from some levels of flooding. However, levees impose construction, operation and management costs which we also do not tally. Built infrastructure also creates a “levee effect”, inducing complacency and encouraging risky development [24] which can lead to even greater damage costs if and when levees fail. Use of built infrastructure in certain areas of the floodplain also exaerbates flood risk elsewhere, which could increase damage costs beyond what we have estimated in this analysis[25]. Additionally, our analysis does not incorporate projected climate change impacts on flooding, which are expected to increase the frequency and severity of floods in some areas of the US[26, 27], likely exacerbating damages. Finally, our estimates of the benefits of floodplain conservation focus solely on avoided damages, undervaluing other ecosystem services related to water quality, carbon sequestration, provision of habitat, and conservation of the option value of future development in places where the benefit-cost calculation changes over time[28, 29].

This analysis demonstrates for the first time that targeted conservation of natural lands in floodplains to avoid potential development is an economically beneficial strategy to mitigate future flood risk in the US. This strategy would not be viable or appropriate everywhere yet could be utilized to a much greater extent than currently in combination with other flood risk reduction efforts. The impacts of flooding are context-specific and local, and the high resolution of the flood and economic data we employ enable identification of specific areas where floodplain protection yields strong net economic benefits. Ongoing development in floodplains globally and the lack of stringent floodplain zoning and development regulations in many countries suggest that similar analyses would yield comparable results in other areas of the world. These findings can inform proactive and integrated flood risk management and efforts to steer development out of harm’s way could complement use of flood defenses and other risk reduction measures and generate net economic benefits to society.

METHODS

Flood Hazard Model

The hazard layers of the CONUS used in this analysis, representing fluvial flooding in river basins larger than 50 km^2 and pluvial flooding everywhere, are detailed in Wing et al.[12]. The underlying terrain is represented by a Digital Elevation Model (DEM) derived from the US Geological Survey (USGS) National Elevation Dataset (NED) at 1 arc second (~30 m) resolution. The HydroSHEDS global hydrography dataset[30] delineates the river network. Channels wider than the grid resolution (~30 m) are burned directly into the DEM, while smaller streams are represented using the subgrid method of Neal et al.[31]. Known flood defenses from the US Army Corps of Engineers (USACE) National Levee Database are also burned into the DEM. The fluvial model component involves driving design discharges of given probabilities through the HydroSHEDS-derived channels and over the NED-derived floodplain using the inertial form of the shallow water equations in two dimensions (based on the LISFLOOD-FP numerical model[32, 31]). These design discharges are based on river gauge records, and the issue of ungauged catchments is addressed by applying a global regionalized flood frequency analysis (RFFA)[33]. The principle of the RFFA methodology is that data from gauged catchments can be transferred to ungauged ones. Catchments are grouped into homogenous clusters based on upstream annual rainfall, land area and climatology, and it is assumed that catchments within each group share similar flood frequency behavior. Using their mean annual flood and growth curves, every river reach in the CONUS has ten design discharges of a given probability calculated between 20% AEP (so-called 1 in 5-year recurrence interval) and 0.2% AEP (so-called 1 in 500-year recurrence interval).

The pluvial component of the hazard model simulates flooding resulting from intense rainfall directly onto the land surface. As with the design discharges, ten return period rainfall scenarios are generated using Intensity-Duration-Frequency (IDF) relationships defined by the National Oceanic and Atmospheric Administration (NOAA). Similar to the RFFA-derived discharges, the IDF data are clustered based on their climatology and upstream annual rainfall so that each grid cell in the DEM has a design rainfall scenario. Using a modified Hortonian equation of Morin and Benyamini[34] and the Harmonized World Soil Database of the Food and Agriculture Organization of the United Nations (FAO), the pluvial model accounts for the infiltration of this rainfall into the ground. The drainage of water in developed areas is also accounted for. A drainage design standard is assumed based on the intensity and duration of the rainfall scenario as well as the degree of urbanization, inferred from the satellite luminosity data of Elvidge et al.[35]. River catchments smaller than 50 km^2 in land area are simulated in the pluvial, rather than fluvial, model component for a number of reasons: i) flood hazard on these small streams is characterized by a flashy response to intense and localized rainfall, better captured by the pluvial model; ii) the availability river flow data for these small streams is limited; and iii) their representation in the RFFA is unsuitable owing to their heterogenous flow behavior.

The fluvial and pluvial model components are used in conjunction to form a single integrated hazard layer for each return period. Each grid cell in this layer represents the maximum water depth of either component. Pluvial water depths smaller than 0.15 m are ignored; a threshold commonly used for surface water masks[36, 12]. These hazard layers are intersected with an array of spatial data, which are described in the following paragraphs.

ICLUS future land-use projections and land-use land-cover data

We integrated multiple publicly-available spatial data layers to identify floodplains at risk for potential development where land acquisition could be a cost-effective flood damage reduction strategy. Future projections of potential development in the CONUS have been generated by the US Environmental Protection Agency (EPA) Integrated Climate and Land-Use Scenarios (ICLUS) project[37]. Based on assumptions relating to future technological innovations, fertility rates and migration patterns, possible maps of land-use in the CONUS have been generated for future scenarios, known as Shared Socio-economic Pathways (SSPs), for each decade up to 2100. The various future scenarios not only differ in the amount of projected population growth and associated area of development, but they also provide different spatial projections about where development may occur. In this study, we focus analysis on SSP2: the most-likely scenario where population growth tracks the US Census Bureau projection and historical migration patterns continue.

Using the National Land Cover Database (NLCD) of the Multi-Resolution Land Characteristics Consortium (MRLC[38]) and USGS Protected Areas Data (PADUS), the total area of floodplains currently in unprotected natural land cover can be ascertained. In conjunction with the future land-use maps, we have used this information to estimate which future developments are 'new'; that is, a floodplain currently in unprotected (as per PADUS), natural land cover (as per the NLCD) that is projected to be developed (as per ICLUS).

Economic Assessment of Flood Damages

We quantified the economic losses of flood damages estimated to occur as a result of projected future development. Economic values (in 2018 USD) were assigned to particular 'developed' land-use classes. The Federal Emergency Management Agency (FEMA) National Structure Inventory contains information on buildings in the CONUS. The location and value of these structures has been intersected with the National Land Use Dataset (NLUD) of the present-day[13], thereby producing an average value per pixel of different classifications. Iterating these values across the future land-use maps means that the economic value of developments on currently unprotected natural land can be estimated. To generate an idea of actual damages that may occur to these assets as a result of flooding, relative depth-damage relationships are applied. These relationships are based on empirical and synthetic damage data collated by the USACE. Different damage functions are applied depending on the type of development: residential, commercial, institutional, industrial or transportation. Using these relationships between the water depth and the economic value in a particular cell produces an expected damage from a certain return period flood.

Expected yearly damages, or average annual loss (AAL), is the integral of the probability-damage curve[39]. We calculate the AAL using the formula:

$$AAL = \int_{0.001}^{0.2} L(f)df$$

where L is the economic loss as a function of each flood frequency f, calculated for all probability flood events between a 20% AEP (5-year) and 0.1 % AEP (1000-year) flood events. We calculated the AAL of developments projected to be built in currently natural unprotected floodplain land at each decadal time step to 2070. Yearly AALs were calculated by interpolating between those at each of the decadal time steps. To estimate the value of all future avoided flood losses we calculated the Present Value (PV) using the formula:

$$PV_L = \sum_{n=1}^{N} \frac{AAL_n}{(1+r)^n}$$

Where AAL_n is the average annualized loss for year n and r is the annual discount rate. We applied three discount rates – 2.75%, 5% and a declining social discount rate – to ensure our conclusions are robust to multiple justifiable economic assumptions. In the US, federal water resources projects use discount rates which are determined by Section 80(a) of the Water Resources Development Act (WRDA) of 1974; Congressional Research Service (2016) and the Water Resources Council's Principles and Standards for Planning Water and Related Land Resources Projects, established pursuant to the Water Resources Planning Act (WRPA) of 1962 (42 U.S.C.). In FY2018, applicable regulations under both laws set the water resources planning discount rate for US Army Corps of Engineers projects at 2.75 percent (Natural Resources Conservation Service 2017). The WRDA/WRPA-prescribed fixed rate of 2.75 percent was used as our baseline discount rate, however, to explore the sensitivity of our findings to changes in the discount rate, we also ran our analysis with two additional rates. First, we used a fixed real social discount rate (SDR) of 5 percent, to better capture the social opportunity cost of capital and which a recent analysis suggests is a better approximation of private returns for the US than the Office of Management and Budget’s 7 percent rate[40]. The second is a certainty-equivalent social time preference-based SDR for long-lived projects estimated by Freeman et al.[41], which is based on historical US interest rates and starts at 4 percent, declining to 2.75 percent in year 25 and 2.5 percent in year 50. We applied these discount rates to sum the AALs up to the years 2050 or 2070, respectively, to calculate the present value of the total expected future damages to such developments up to each of those target years.

Economic Assessment of Acquisition Costs

To estimate the costs of avoiding future potential flood damages we calculated the costs of acquiring land at risk for development. We estimated the average acquisition cost in three steps, incorporating actual acquisition costs of land for conservation, agricultural land values, developed residential land values, economically optimal lot sizes, and plattage effects.

Step 1: Acquisition Size

The optimal lot size for a housing producer decreases with the price of land, and as the price of land falls with distance from the economic center of the area, the average lot size increases[42-45]. The relation between our acquisition lot size and the land price can be expressed as a linear function using county-level (j) land price data and parcel-level (ij) parcel size. Values for $Land\ Price_j^*$ are from estimates external to the parcel-level transactions database.

$$\ln Area_{ij} = a + b \ln Land\ Price_j^* + e_i$$

In the equation above, the (log) area of the purchased parcel is expressed as a function of a constant term, a, the (log) price per unit of area multiplied by a coefficient, b, and a residual, e.

When the parameters are estimated using OLS estimation, the resulting estimates, $\hat{a}$ and $\hat{b}$ are then used to predict the acquisition lot sizes for different counties, as $\ln \widehat{Area}_{ij} = \hat{a} + \hat{b} \ln Land\ Price_i$. This acquisition lot size is then used in the next two steps of the method.

Step 2: Plattage Adjustment

Within an area, variation around the optimal lot size is associated with variations in the land price per acre, a phenomenon referred to as a "plattage effect". Plattage effects reflect variation in lot quality, with smaller lots typically of higher average quality and larger lots of lower average quality. Plattage effects are eliminated using a regression approach following Davis et al.[46]. This model estimates the price of a lot as a function of submarket fixed effects (to control for optimal lot size) and the lot size of the parcel.

$$\ln Land\ Price_{ij} = \alpha_j + \beta \ln Area_{ij} + \gamma \ln Land\ Price_j^* + \epsilon_i$$

The estimates from step 1 can be nested into this specification to transform $Area_{ij}$ into a relative measure. While transformation is not necessary asymptotically, it reduces the number of estimated parameters substantially, and is thus more efficient in small samples.

$$\ln Land\ Price_{ij} = \alpha + \beta(\ln Area_{ij} - \ln \widehat{Area}_{ij}) + \gamma \ln Land\ Price_j^* + \epsilon_i$$

Step 3: Average Acquisition Cost

Using the estimates in steps 1 and 2, average acquisition cost per acre can be estimated for each county as

$$\widehat{Land\ Price}_j = \exp(\hat{\alpha} + \hat{\beta} \ln \widehat{Area}_j + \hat{\gamma} \ln Land\ Price_j^*)$$

We used a database of 1,405 land purchases by The Nature Conservancy (TNC) between 2009 and 2018 to build a model that predicts the average cost of land acquisition for conservation. We built a model rather than directly using the average observed purchase costs for particular areas because: 1) we did not have observed land purchases in every county in the CONUS; 2) purchase price varies based on parcel size and a model was required to correct for this (as described below); 3) there is large variation in individual purchase prices and using a model reduces the noise that would otherwise be introduced by outlier individual purchases.

County-level land price data are from two sources. The first is average farmland values by county from the 2017 Census of Agriculture produced by the US Department of Agriculture[15]. The second source is land underneath single-family residential structures found in Davis et al.[16]. This source measures the value of already-developed parcels which presumably are more desirable and higher-value than land that is currently undeveloped. To counteract this upward bias in our estimate, we use the minimum tract-level land price per acre within a county as the county-level value. In both the agricultural and residential land databases, there are missing values, because there are too few farms in an area to produce an estimated agricultural value, or too few single-family housing units in an area to produce a residential value. To arrive at an estimated value for every county in the nation, a chained predictive-mean-matching imputation algorithm is used. Additional variables used in the imputation algorithm are from the

American Community Survey for the pooled 2013-2017 sample. These variables include the median home value (log), the population (log), the average structure age (log), the residential structure type, state fixed effects, and imputation fixed effects representing whether or not the agricultural or the residential land is in the process of being imputed.

The steps described above were implemented using agricultural land in the optimal lot size model (Model 1) and both the agricultural and residential data separately as $Land\ Price_j^*$ in the plattage model (Model 2) (Table SI4 and Figure SI5). Parcels with easements are included in Model 1 but dropped from Model 2 because they provide information on the price-acquisition size relation but do not reflect the kind of land that is the subject of the benefit-cost exercise carried out in this study. In Model 1, as predicted, the acquisition lot size in the TNC data falls with the agricultural land price per acre. In Model 2, both the agricultural and residential land price per acre is predictive of the acquisition land price. The plattage effect is negative, with parcel sizes in excess of the predicted county-level optimum facing a discount, and parcel sizes smaller than the optimum priced at a premium. Estimates from Model 2 are used to estimate the acquisition land price per acre used in this study.

We quantified acquisition costs in multiple zones: the 20% AEP (5 year), 5% (20 year), 2% (50 year), 1% (100 year), and (500 year) floodplains, as well as the differential areas between them (e.g. the 2% zone minus the 5%). Comparing the costs of land acquisition to the potential damages flooding may cause to future developments will give some indication, in economic terms, of the benefits of targeted floodplain conservation. If such areas are conserved and projected developments do not occur, then the calculated damages up to 2050 and 2070 can be considered ‘mitigated’. The BCR of mitigated damages to acquisition costs will indicate whether a certain acquisition zone within a certain county is cost-effective (BCR > 1) or not (BCR < 1).

Data Availability

Publicly available data:

- USGS National Elevation Dataset: http://www.ned.usgs.gov
- HydroSHEDS: http://www.hydrosheds.org
- USACE National Levee Database: http://www.nld.usace.army.mil
- FEMA National Structure Inventory: http://data.femadata.com/FIMA/NSI_2010
- MRLC National Land Cover Database: http://www.mrlc.gov/nlcd2011.php
- USGS PAD-US: http://gapanalysis.usgs.gov/padus
- Theobold (2014) National Land-Use Dataset: http://csp-inc.org/public/NLUD2010_20140326.zip
- EPA ICLUS scenarios: http://www.epa.gov/iclus
- FAO Harmonized World Soil Database: http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en
- NOAA Intensity-Duration-Frequency curves: http://hdsc.nws.noaa.gov/hdsc/pfds
- Elvidge et al. (2007) satellite luminosity data: http://www.ngdc.noaa.gov/eog
- USDA Census of Agriculture: https://www.nass.usda.gov/Quick_Stats/index.php
- FHA residential land price data: https://www.fhfa.gov/PolicyProgramsResearch/Research/Pages/wp1901.aspx

Data available for non-commercial academic research purposes:

- Flood hazard data: contacting Christopher Sampson at Fathom Ltd. (c.sampson@fathom.global)
- Hydraulic model, LISFLOOD-FP: http://www.bristol.ac.uk/geography/research/hydrology/models/lisflood/downloads/
- Global Runoff Data Center discharge data: http://www.bafg.de/GRDC/EN/01_GRDC/12_plcy/data_policy_node.html

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Author Contributions

K.A.J, O.W., P.B., J.E.F., T.K., C.S., and A.S. designed the research. O.W., T.K., W.L., J.E.F. and K.A.J. completed analyses. K.A.J. drafted the manuscript. All authors discussed the results and edited and commented on the manuscript.

Competing Interests

K.A.J., J.E.F, T.K., and W.D.L. have no competing interests. O.W., P.B., C.S., and A.S. have an interest in or are employed by Fathom, a flood analytics company based in the UK.

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Annual Exceedance Probability Flood Zone	Cumulative area of unprotected natural floodplain (km^2)	Area of additional unprotected natural floodplain (km^2)	Area of additional unprotected natural floodplain with BCR > 1 (km^2)	Benefit:cost ratio for additional floodplain area	Cumulative benefit:cost ratio
20% (5 yr)	371,129	371,129	124,559	1.30	1.30
5% (20 yr)	529,915	158,786	102,249	4.33	2.18
2% (50 yr)	617,011	87,096	29,553	1.39	2.07
1% (100 yr)	675,919	58,908	6,750	0.49	1.94
.2% (500 yr)	824,112	148,193	4,841	0.23	1.64

Table 1. **Total area of unprotected natural floodplain, area where avoided flood damages exceed acquisition costs, and benefit-cost ratios for acquiring additional unprotected natural floodplain areas. Areas and benefit-cost ratios calculated for development projected under SSP2 by 2070 using a 2.75% discount rate.**

Annual Exceedance Probability Acquistion Area	**2050**			**2070**		
	2.75%	**5%**	**Variable**	**2.75%**	**5%**	**Variable**
20% (5 yr)	31%	22%	29%	42%	28%	40%
5% (20 yr)	44%	35%	43%	55%	41%	53%
2% (50 yr)	44%	40%	42%	54%	40%	52%
1% (100 yr)	42%	38%	40%	52%	38%	50%
.2% (500 yr)	38%	34%	36%	48%	34%	46%

Table 2. **Percentage of US counties with BCR > 1 by 2050 and by 2070 calculated using three different discount rates.**

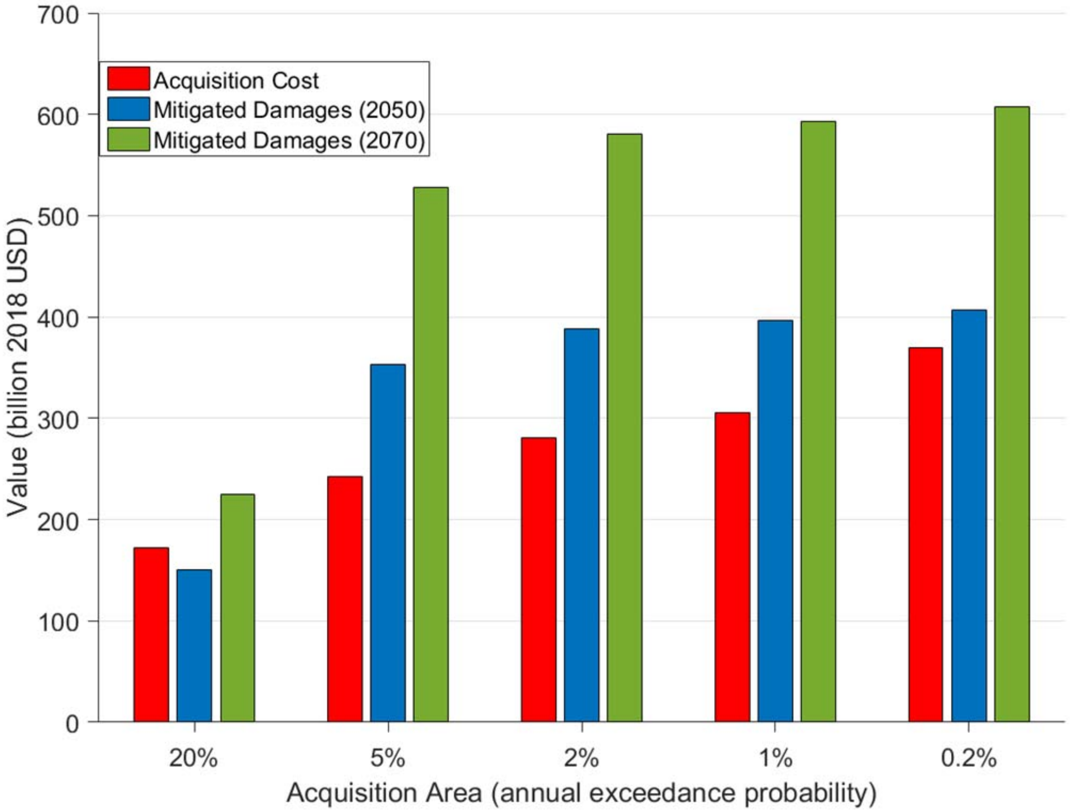

Figure 1. **Costs to acquire unprotected natural floodplain areas for each of five annual exceedance probability flood zones and the present value of future damages mitigated by avoiding development in each floodplain**.

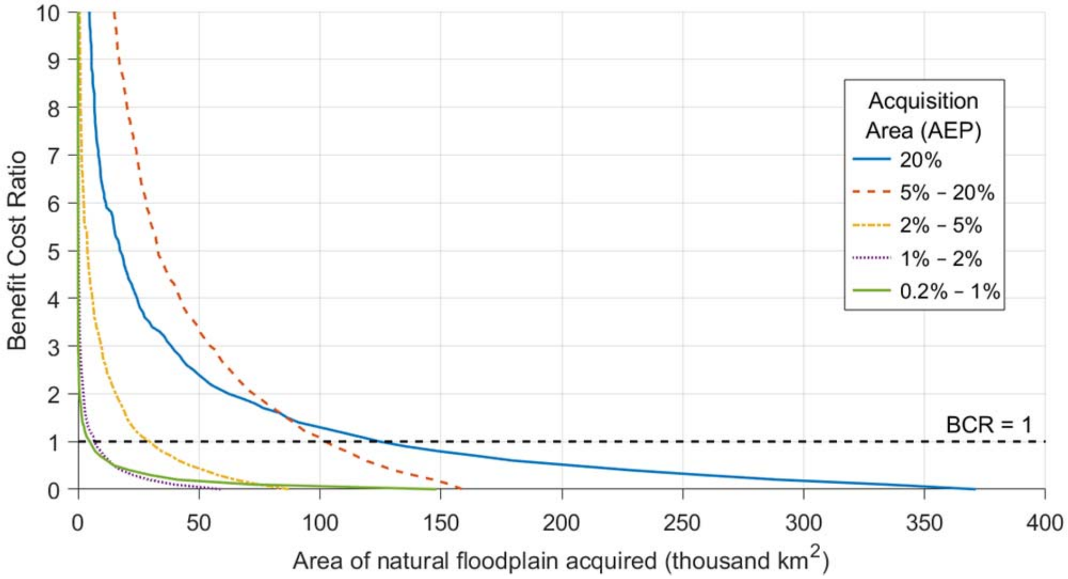

Figure 2. **The area of each additional return period acquisition zone that exceeds a certain benefit-cost ratio (BCR). For instance, the 20% AEP (5 yr) floodplain has 17,328 km^2 with BCR > 5, 38,495 km^2 with BCR > 3 and 124,559 km^2 with BCR > 1.**

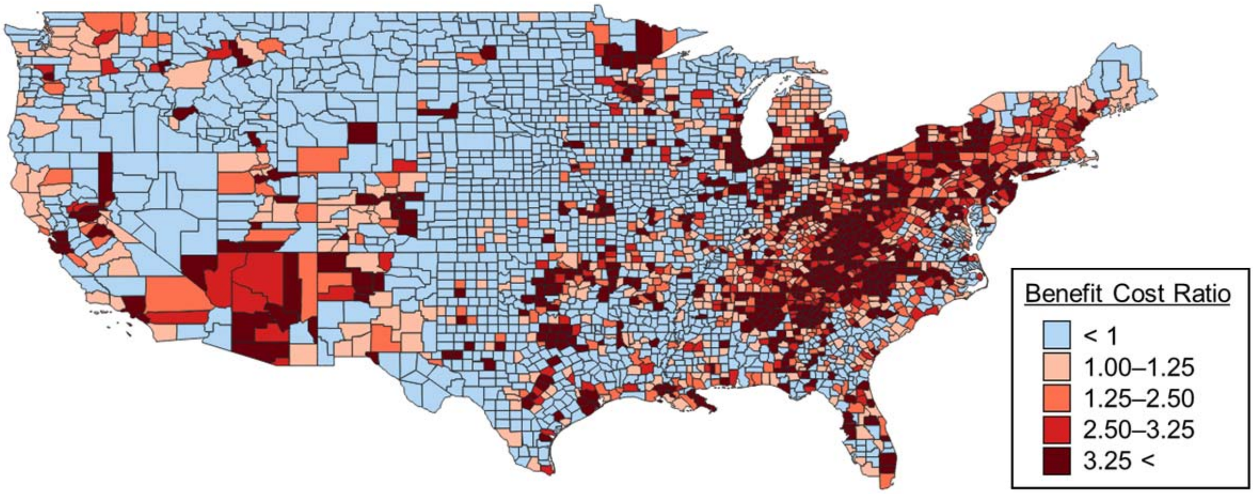

Figure 3. **Map of counties and associated benefit-cost ratios for the strategy of acquiring natural lands in 1% AEP (100-yr) floodplain to avoid future projected flood damages up to 2070 using a 2.75% discount rate.**

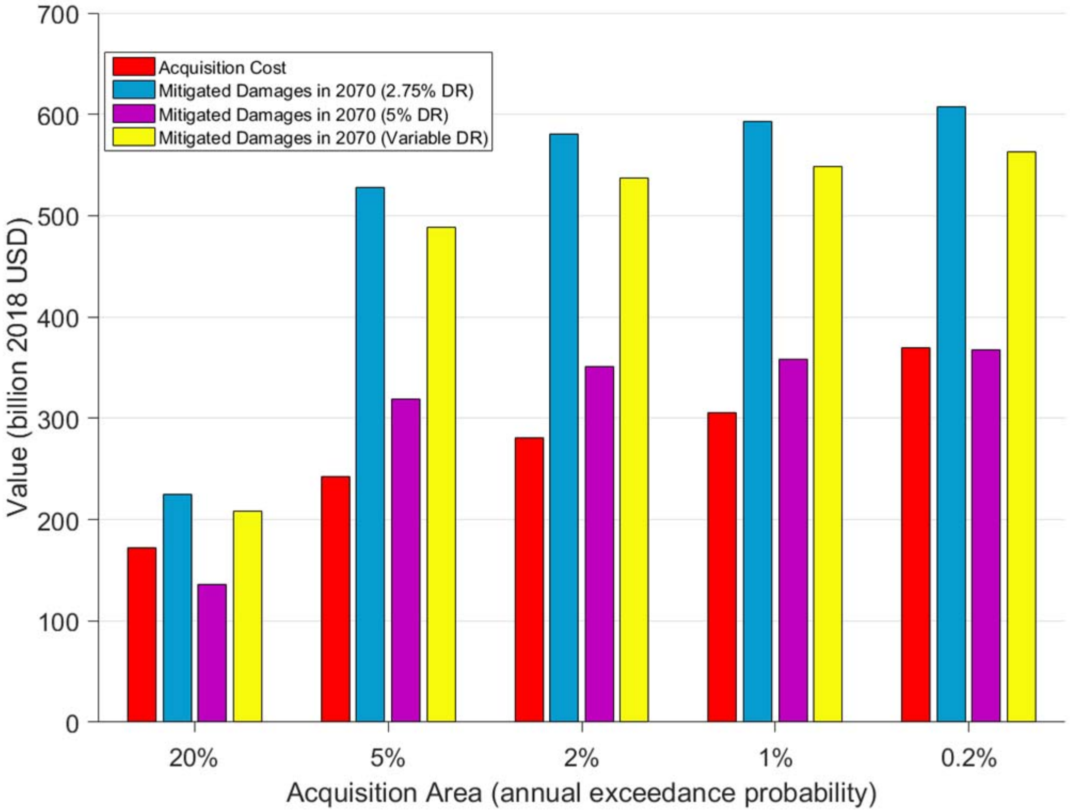

Figure 4. **Costs to acquire unprotected natural floodplain areas for each of five annual exceedance probability flood zones and the present value of damages mitigated by 2070 calculated using three different discount rates.**

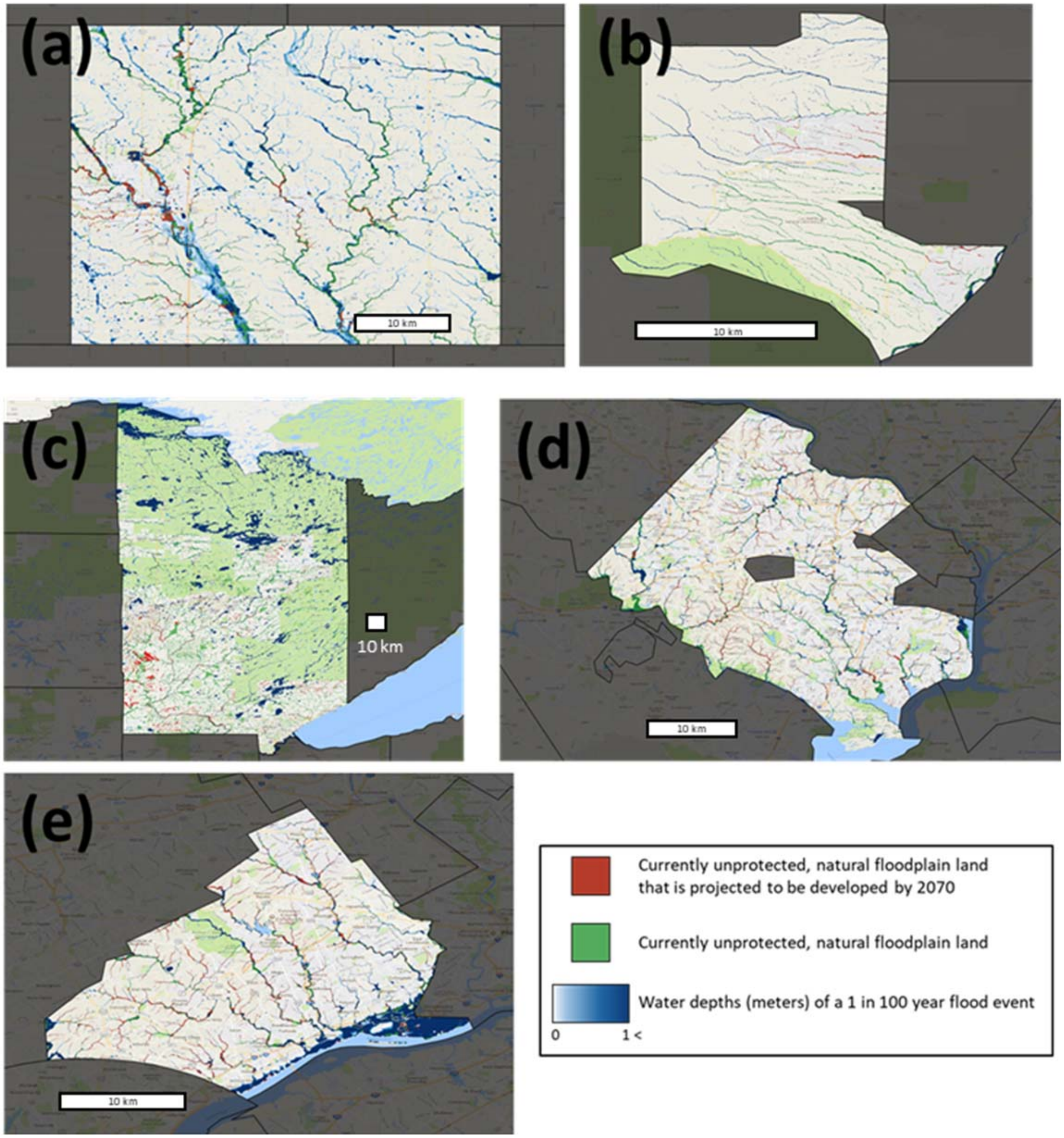

Figure 5. Maps of selected counties showing the 1% AEP floodplain, unprotected natural floodplain land and areas projected to be developed by 2070 within it. (a) Story County, IA: avoided damages = $820M; acquisition costs = $61M; BCR = 13.4; (b) Los Alamos County, NM: avoided damages = $22M; acquisition costs = $6.5M; BCR = 3.4; (c) St Louis County, MN: avoided damages = $3.4Bn; acquisition costs = $362M; BCR = 9.5; (d) Fairfax County, VA: avoided damages = $1.1Bn; acquisition costs = $150M; BCR = 7.0; (e) Delaware County, PA: avoided damages = $403M; acquisition costs = $45M; BCR = 9.0.